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Study on Absorption Performance at High Liquid Loads using a Novel Random Packing: Super Mini Ring

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Abstract: The Super Mini Ring (SMR), a novel random packing, has found wide application in liquefied petroleum gas purification and carbon dioxide absorption as it has particularly good performance at high liquid loads. In this study, the hydrodynamic and mass transfer models for this type of packing were studied and compared over a wide range of liquid loads ($L_W = 0–220\,m^3 \cdot m^{-2} \cdot h^{-1}$). The modified Billet and Schultes pressure equation was found to be superior to other models presented in the literature. Models used to calculate the flooding gas velocity and the height of the mass transfer unit for the SMR have also been presented.

Keywords: Hydrodynamics, mass transfer, modified Billet and Schultes equation, super mini ring

INTRODUCTION

Random packings have been widely used in industrial processes such as solvent extraction, high pressure distillation and gas absorption with high liquid loads (1). Significant efforts have been dedicated to developing new, high-efficiency random packings for decades (2,3). It has been shown that some random packings with complicated structures do not

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behave very well, while Super Mini Ring (SMR), a novel random packing, has good performance because of its elaborate design of the twisting-inwards arc units (4). The SMR has been widely used in carbon dioxide absorption of synthetic ammonia plants and LPG (liquefied petroleum gas) purification with significant economic benefits (5,6).

The main features of the SMR can be seen in Fig. 1. With the twisting-inwards arc units, its rigidity has been remarkably increased and the dispersion, aggregation and re-dispersion of liquid drops have been greatly promoted. This packing, by means of the small height-diameter ratio, enhances the mass transfer rate between the contacting phases, simultaneously decreasing the pressure drop in the column, increasing the specific surface area, and accelerating the surface renewal. Experiments have shown that when SMR packing is used for a gas-liquid mass transfer process, its performance is better than Mellapak, Intalox Saddles and Pall rings, which are still used in industry (7,8). For processes where SMR packings have been used to recover CO_2 from flue gases, the height of the absorption column was reduced by 20% relative to a pall ring packed column (9). A reduction in the height of the lamellas forming the packing elements leads to an increase in the packing efficiency (10).

In order to develop a reliable design method for this type of packing, Pan et al. (8) discussed the hydrodynamic and mass transfer performance using Φ38 mm SMR for liquid loadings (L_W) from 0–50 $m^3 \cdot m^{-2} \cdot h^{-1}$. Sun et al. (11) studied the performance of Φ16 mm and Φ25 mm SMR at $L_W = 0\text{–}121\, m^3 m^{-2} h^{-1}$ and presented correlations for pressure drop and height of a mass transfer unit. Sun et al. (11) also regressed the Bain and Hougen flooding velocity equation (12). Due to the increasing

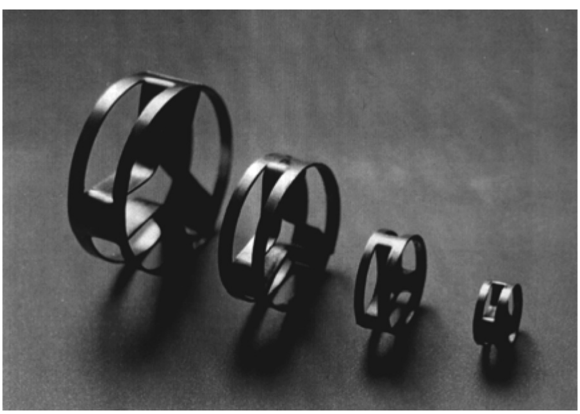

Figure 1. Appearance of Super Mini Ring (SMR).

use of SMR packing in industrial processes and especially for gas-liquid absorption under high liquid loads, it is necessary to understand its performance over a range of operating conditions. In particular the hydrodynamic and mass transfer performance of the SMR at high liquid loads needs to be investigated and further improvement is required in the design methods of packed columns equipped with the SMR packing.

HYDRODYNAMICS AND MASS TRANSFER MODELS

Billet and Schultes (13), Takahashi et al. (14) and Bemer and Kalis (15) have carried out studies on the hydrodynamic and/or mass transfer models for a range of randomly packed columns.

Billet and Schultes (13) assumed the empty space in the packings provided vertical flow channels, through which the liquid trickled evenly distributed downwards while the gas flowed upwards in the counter flow. However, the flow channels actually deviated from the vertical and were determined by the shape of the packings. Because the geometrical shape of the flow channels is defined by a range of factors, not only the surface area or the void volume, the model postulated that the deviation of the real flow behavior of the phases from the vertical flow channels in packed columns could be expressed by the packing-specific shape

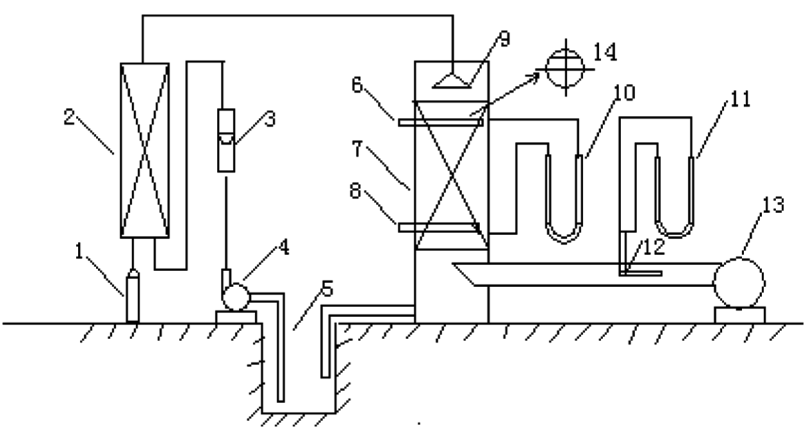

Figure 2. The experimental set-up and flow scheme (1) oxygen cylinder, (2) oxygen absorbing column, (3) liquid rotameter, (4) centrifugal pump, (5) sump, (6) and (8) sample connection point, (7) packed column, (9) liquid distributor, (10) and (11) U-tube manometer, (12) pitot tube, (13) centrifugal blower, (14) cross section of sampling tube.

Table 1. Geometric characteristics of packings

Type of packing	Diameter × height mm	Specific surface area $m^2 \cdot m^{-3}$	Voidage $m^3 \cdot m^{-3}$
Φ50 mm SMR	50 × 17	122	0.965
Φ25 mm SMR	25 × 9.0	228	0.935
Φ16 mm SMR	16 × 5. 5	348	0.923

constants. The model proposed by Billet and Schultes was shown to apply to a range of random or structured packings. It made it possible to determine the mass transfer efficiency, the pressure drop, the column holdup and the load limits on the basis of a uniform theory (13). Furthermore, Takahashi et al. (14) reported that the total pressure drop could be expressed as the sum of the dry pressure drop and the wet pressure drop. The dry pressure drop originated mainly from the friction

Table 2. Pressure drop models for packed column

Author	Pressure drop models
Billet and Schultes (13)	$\frac{\Delta p_0}{H} = \psi_0 \frac{a}{(\varepsilon - h_L)^3} \frac{F_V^2}{2} \frac{1}{K}$
	$h_L = \left(\frac{12}{g} \frac{\eta_L}{\rho_L} u_L a^2 \right)^{1/3} \quad (u_V \leq u_{V,S})$
	$h_L = h_{L,S} + (h_{L,Fl} - h_{L,S}) \left(\frac{u_V}{u_{V,Fl}} \right)^{13} \quad (u_V \geq u_{V,S})$
	$h_{L,Fl}^3 (3h_{L,Fl} - \varepsilon) = \frac{6}{g} a^2 \varepsilon \left(\frac{\eta_L}{\rho_L} \right) \frac{L}{V} \frac{\rho_V}{\rho_L} u_{V,Fl} \quad \left(\frac{\varepsilon}{3} \leq h_{L,Fl} \leq \varepsilon \right)$
Pan et al. (8)	$\frac{\Delta p_d}{H} = A \cdot F_V^B; \quad \frac{\Delta p_W}{H} = C \cdot 10^{D \cdot L_W} \cdot F_V^E$
Takahashi et al. (14)	$\frac{\Delta p_0}{H} = 2f[u_V^2/\varepsilon]\rho_V/d_p;$
	$Re_G < 200, f = 114\ Re_G^{-0.742}; Re_G \geq 200, f = 6.85\ Re_G^{-0.216}$
	$\frac{\Delta p_0}{H} = 2f[u_V^2/(\varepsilon - h)]\rho_V/d_p + kh^3(u_V/(\varepsilon - h))^2$
	$h = \left[1.53 \times 10^{-4} + 2.90 \times 10^{-5} \varepsilon\ \mathrm{Re}_L^{0.66} (\eta_L/\eta_W)^{0.75} \right] d_p^{-1.20}$
Bemer & Kalis (15)*	$\frac{\Delta p_0}{H} = \frac{0.29\phi^{-2}\rho_g u_V^2 a}{\varepsilon^3}$
	$\frac{\Delta p_0}{H} = \frac{0.29\phi^{-2}\rho_g u_V^2 a}{\varepsilon^3} \left(1 - \frac{h}{2x^{5/3}\phi\varepsilon} \right)^{-5}; \ h = 0.34a \left(\frac{u_L}{a} \right)^{2/3}$

*Suitable in the range below the loading point.

Table 3. The parameters & deviations of pressure drop models for packed column

Author	Packings	Parameters	Dry pressure drop		Wet pressure drop	
			S.D.	Avg.	S.D.	Avg.
Billet and Schultes (13)	Φ50 mm SMR	$C_{P,0} = 0.519$	1.82%	1.79%	34.4%	38.6%
	Φ25 mm SMR*	$C_{P,0} = 0.624$	2.17%		35.9%	
	Φ16 mm SMR*	$C_{P,0} = 0.743$	1.38%		45.3%	
Pan et al. (8)	Φ50 mm SMR	A = 31.856; B = 2.013; C = 15.131; D = 0.0085; E = 3.072	0.75%	2.23%	14.9%	18.6%
	Φ25 mm SMR*	A = 93.339; B = 1.949; C = 92.037; D = 0.0085; E = 2.755	3.51%		21.5%	
	Φ16 mm SMR*	A = 191.446; B = 1.890; C = 257.811 D = 0.0081; E = 2.587	2.44%		19.3%	
Takahashi et al. (14)	Φ50 mm SMR	k = 11.928	25.8%	28.8%	64.5%	
	Φ25 mm SMR*	k = 19.266	24.2%		55.8%	
	Φ16 mm SMR*	k = 33.767	36.3%		56.5%	
Bemer and Kalis (15)	Φ50 mm SMR	Φ = 1.034; x = 0.427	0.86%	2.8%	17.6%	10.7%
	Φ25 mm SMR*	Φ = 0.939; x = 0.544	3.6%		8.5%	
	Φ16 mm SMR*	Φ = 0.825; x = 0.648	3.8%		5.9%	
This paper	Φ50 mm SMR	$\theta_1 = 1.235 \cdot a^{-0.0533} \cdot \varepsilon^{-1.265}$; $\theta_2 = -3278.3 \cdot a^{893.8} \cdot \varepsilon^{23345}$			15.2%	13.0%
	Φ25 mm SMR*				11.8%	
	Φ16 mm SMR*				11.9%	

*Experimental data from Sun et al. (11).

of gas rising through the void of the packed bed and was expressed by the Fanning equation. The wet pressure drop increased with the net gas velocity, because of the presence of liquid holdup in the packed bed, and therefore it was expressed as a function of liquid holdup, gas velocity, etc. Takahashi et al. (14) obtained a new correlation for the pressure drop in randomly packed columns using experimental data from many previous studies. Bemer and Kalis (15) regarded the flow of the liquid in a packed bed as the flow in a collection of channels. Dry pressure drop could then be predicted using the straight and winding channel models, while the wet pressure drop below the loading point could be predicted using a model based on a number of equal, round channels with constrictions. Comparison of the dry and wet pressure drop relations with published experimental data for different random packings gave satisfactory agreement.

In this study, we have investigated the above hydrodynamic and mass transfer models as well as the research presented by Pan et al. (8) and Sun et al. (11) at high liquid loads ($L_W = 0–220\,m^3\,m^{-2}\,h^{-1}$) and the modified the Billet and Schultes pressure drop equation for the SMR packing.

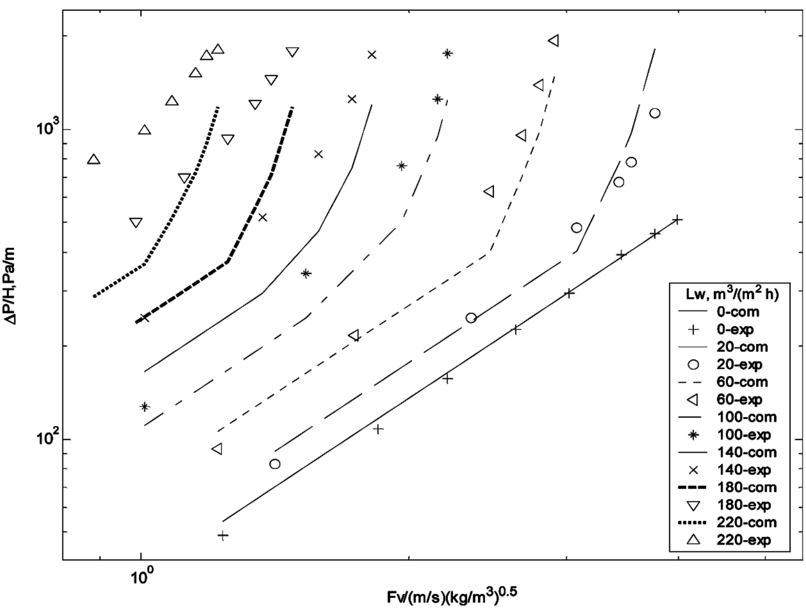

Figure 3. Comparison of pressure drop calculated from Billet and Schultes model with those determined in the experiment for Φ50 mm SMR.

EXPERIMENTAL PROCEDURE

Experiments were performed in a 600 mm diameter column with an air-oxygen-water system at atmospheric pressure. The height of the packed bed was 1200 mm. The experimental set-up is shown in Fig. 2. Air and water flowed through the column countercurrently and their flow rates were measured with a pitot tube and liquid rotameter respectively. Pressure drop in the packed bed was measured using U-tube manometers filled with water. The mass transfer performance was studied by stripping oxygen from water which was oversaturated with oxygen. Once steady state conditions were obtained, liquid samples were collected by inserting sample tubes into the base and top of the column. The cross section of the sampling point is shown in Fig. 2. The distance between the two sampling tubes in the packing section is about 1 m. The concentration of oxygen in the samples was measured using an inoLab Oxi Level 2 precision dissolved oxygen meter made by WTW, Germany.

The geometric characteristics of the SMR packings discussed in this study (Φ50 mm, Φ25 mm and Φ16 mm) are listed in Table 1. Experimental data for Φ16 mm and Φ25 mm SMR was taken from Sun et al. (11).

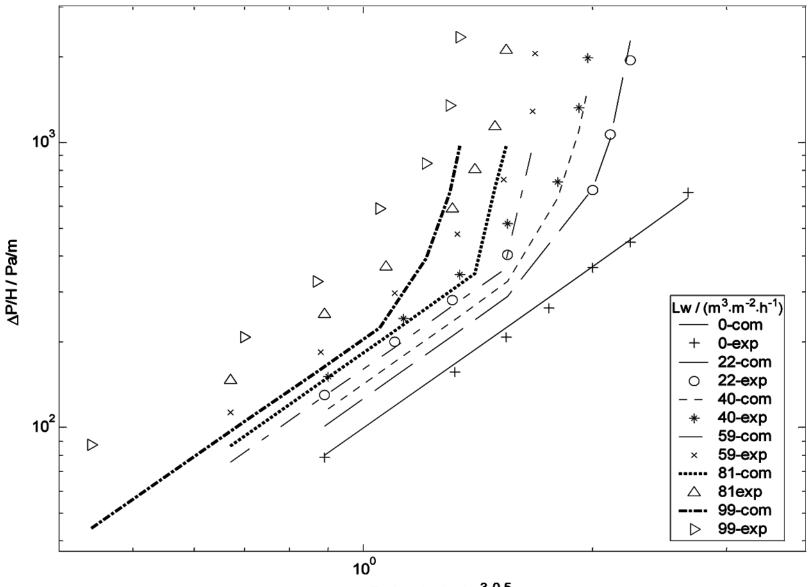

Figure 4. Comparison of pressure drop calculated from Billet and Schultes model with those determined in the experiment for Φ25 mm SMR.

RESULTS AND DISCUSSION

Pressure Drop

Table 2 presents all of the pressure drop equations discussed above in this paper. Table 3 presents the values of the constants for this study which were found by fitting the experimental data from this work and that of Sun et al. (11). The standard deviation (S.D.) has also been calculated with the help of computer software MATLAB. Figures 3, 4 and 5 show the pressure drop curves based on the Billet and Schultes model for Φ 50 mm, Φ 25 mm and Φ 16 mm SMR respectively.

Table 2 and Table 3 show that there are several models available in the literature to predict the pressure drop obtained in this study. The models presented by Bemer and Kalis (15) and Pan et al. (8) provide good predictions with standard deviations of less than 3% for dry pressure drop. The standard deviation for the wet pressure drop predicted by Pan et al. (8) is quite large (18.6%) while the correlations proposed by Bemer and Kalis (15) result in a deviation of 10.7%, however this model is only applicable below the loading point.

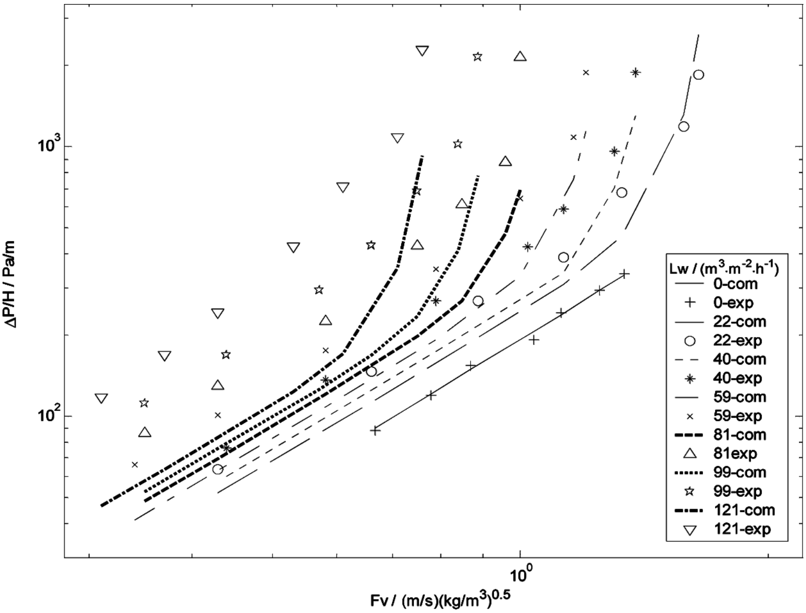

Figure 5. Comparison of pressure drop calculated from Billet and Schultes model with those determined in the experiment for Φ16 mm SMR.

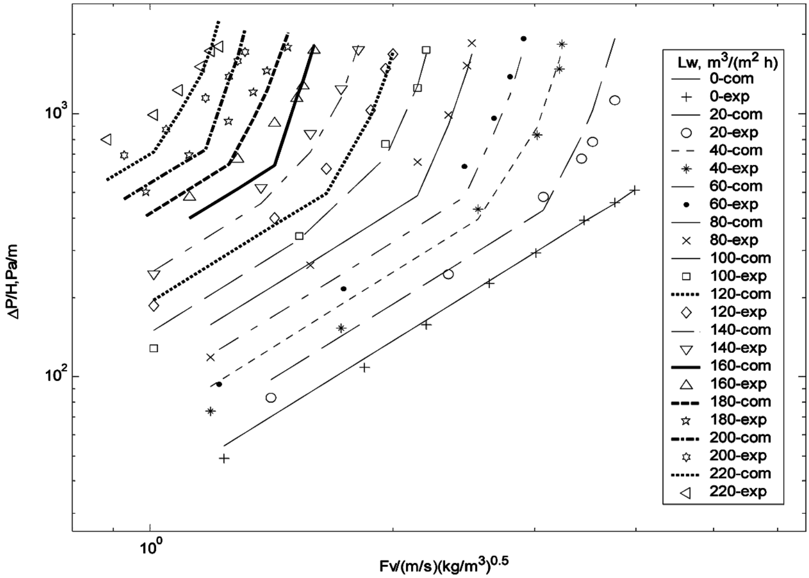

Figure 6. Comparison of pressure drop calculated from modified Billet and Schultes model with those determined in the experiment for Φ50 mm SMR.

The model presented by Takahashi et al. (14) results in very large deviations of pressure drop for both dry plates (28.8%) and wet ones (58.9%).

The model presented by Billet and Schultes (13) has attracted attention from many researchers as an advanced pressure drop prediction model for packed columns with random or structured packings (16–20). It has been shown from the results in this work that this model can be used to calculate the dry pressure drop for SMR with a standard deviation of 1.79%. However, when it is used to predict the wet pressure drop of SMR, the deviation is large (38.6%). Furthermore, the model tends to underestimate the pressure drop as the liquid loads increases. Based on the original Billet and Schultes model, a modified wet pressure drop equation has been presented by Equation (1):

$$\frac{\Delta p_0}{H} = \theta\psi_0 \frac{a}{(\varepsilon - h_L)^3} \frac{F_V^2}{2} \frac{1}{K} \tag{1}$$

Where θ stands for the modified factor for Billet and Schultes model. It is defined as follows:

$$\theta = (\theta_1^{L_W})^{\theta_2} \tag{2}$$

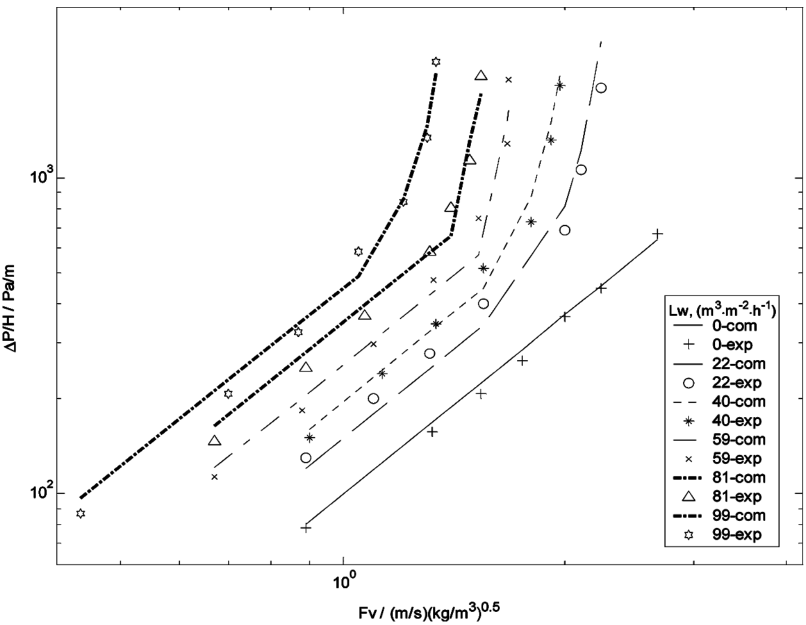

Figure 7. Comparison of pressure drop calculated from modified Billet and Schultes model with those determined in the experiment for Φ25 mm SMR.

Where θ_1 and θ_2 are defined as:

$$\theta_1 = k_1 \cdot a^{k_2} \cdot \varepsilon^{k_3}; \theta_2 = k_4 \cdot a^{k_5} \cdot \varepsilon^{k_6} \tag{3}$$

The constants of the modified Billet and Schultes equation are obtained by fitting the experimental data to this equation and results are provided in Table 3. Figures 6, 7 and 8 show the wet pressure drop curves of the modified Billet and Schultes equation in a packed column equipped with Φ50 mm, Φ25 mm and Φ16 mm SMR respectively. Figure 9 compares several models and correlations for Φ50 mm SMR at $L_W = 140\,m^3\,m^{-2}\,h^{-1}$.

Table 3 shows that the modified Billet and Schultes equation has a deviation of 13.0% between the experimental and predicted wet pressure drop values. This modified correlation provides a better prediction than any of the other correlations and is applicable over the total range of operating conditions used in this study. In particular, this equation has been shown to be applicable at high liquid loads (up to $220\,m^3\,m^{-2}\,h^{-1}$) (see Figs. 6, 7 and 8). Figure 9 further shows that the modified Billet and Schultes equation gives a better prediction for the wet pressure drop, particularly at high liquid loads.

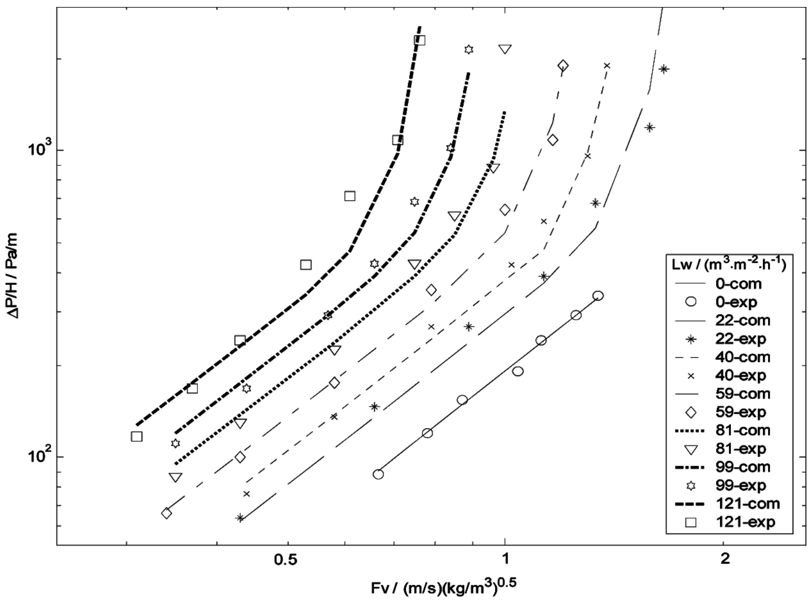

Figure 8. Comparison of pressure drop calculated from modified Billet and Schultes model with those determined in the experiment for Φ16 mm SMR.

Flooding Gas Velocities

Table 4 lists all the models discussed in this paper for predicting the gas velocity at the flooding point. Table 5 provides the values of the constants required for these correlations and compares these models to the experimental data.

Table 5 shows that the Bain and Hougen's equation (12) provides a very good prediction with a small deviation of 0.70% between experimental and predicted values. Therefore this model can be used to predict the flooding gas velocities for the SMR packing.

Mass Transfer

Table 6 lists all of the models discussed in this paper that are available for predicting mass transfer performance in a packed column. Table 7 shows the values of the constants for these correlations and compares the experimental mass transfer data with that predicted by the model.

Results from Table 7 shows that the deviations for the model presented by Billet and Schultes (13) and Sun et al. (11) are 0.72% and

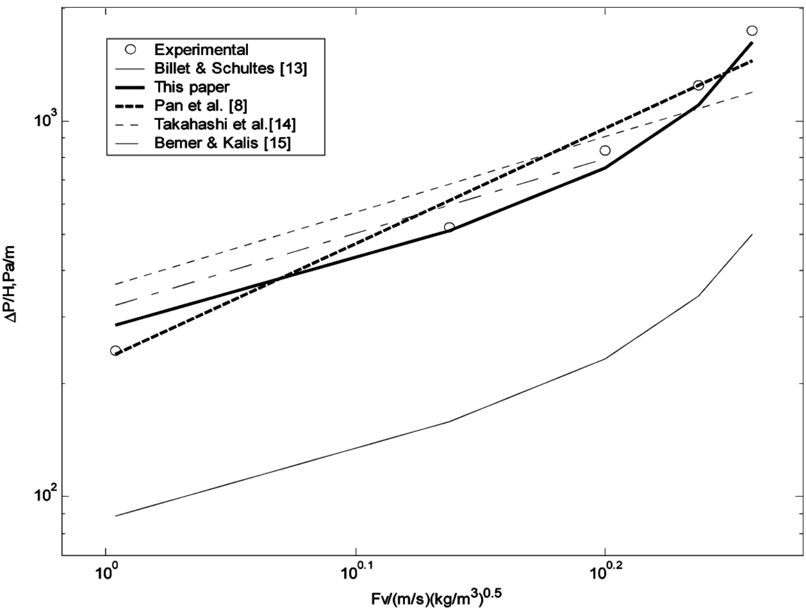

Figure 9. Comparison of pressure drop calculated from several models with those determined in the experiment at $L_W = 140\,m^3 \cdot m^{-2} \cdot h^{-1}$ for Φ50 mm SMR.

Table 4. Flooding gas velocity models for a packed column

Author	Flooding gas velocity models
Billet and Schultes (13)	$u_{V,Fl} = \sqrt{2}\sqrt{\frac{g}{\psi_{Fl}}\frac{(\varepsilon - h_{L,Fl})^{3/2}}{\varepsilon^{1/2}}}\sqrt{\frac{h_{L,Fl}}{a}}\sqrt{\frac{\rho_L}{\rho_v}}$;
	$\psi_{Fl} = \frac{g}{C_{Fl}^2}\left[\frac{L}{V}\sqrt{\frac{\rho_v}{\rho_L}}\left(\frac{\eta_L}{\eta_V}\right)^{0.2}\right]^{-2n_{Fl}}$
	$while\ \frac{L}{V}\sqrt{\frac{\rho_v}{\rho_L}} \le 0.4:\ n_{Fl} = -0.194$
	$while\ \frac{L}{V}\sqrt{\frac{\rho_v}{\rho_L}} \ge 0.4:\ n_{Fl} = -0.708;\ C_{Fl}^0 = 0.6244 C_{Fl}\left(\frac{\eta_L}{\eta_V}\right)^{0.1028}$
	$h_L = \left(\frac{12}{g}\frac{\eta_L}{\rho_L}u_L a^2\right)^{1/3} \quad (u_V \le u_{V,S})$
	$h_L = h_{L,S} + (h_{L,Fl} - h_{L,S})\left(\frac{u_V}{u_{V,Fl}}\right)^{13} \quad (u_V \ge u_{V,S})$
	$h_{L,Fl}^3(3h_{L,Fl} - \varepsilon) = \frac{6}{g}a^2\varepsilon\left(\frac{\eta_L}{\rho_L}\right)\frac{L}{V}\frac{\rho_V}{\rho_L}u_{V,Fl}\left(\frac{\varepsilon}{3} \le h_{L,Fl} \le \varepsilon\right)$
Bain and Hougen (12)	$\lg\left[\frac{u_{V,Fl}}{g}\frac{a}{\varepsilon^3}\frac{\rho_V}{\rho_L}\eta_L^{0.2}\right] = A + B\left(\frac{L}{V}\right)^{1/4}\left(\frac{\rho_V}{\rho_L}\right)^{1/8}$

Table 5. Parameters and deviations of flooding velocity models for packed column

			Flooding gas velocity	
Author	Packings	Parameters	S.D.	Avg.
Billet and Schultes (13)	Φ50 mm SMR	$C_{Fl} = 2.024$	3.58%	4.2%
	Φ25 mm SMR*	$C_{Fl} = 1.929$	2.63%	
	Φ16 mm SMR*	$C_{Fl} = 1.944$	6.41%	
Bain and Hougen (12)	Φ50 mm SMR	$A = -1.469$; $B = -0.767$	0.54%	0.70%
	Φ25 mm SMR*	$A = -1.430$; $B = -0.610$	0.81%	
	Φ16 mm SMR*	$A = -1.299$; $B = -0.673$	0.73%	

*Experimental data from Sun et al. (11).

Table 6. HTU models for packed column

Author	HTU models
Billet and Schultes (13)	$HTU_{OL} = \frac{u_V}{\lambda \beta_V a_{Ph}} + \frac{u_L}{\beta_L a_{Ph}}; \lambda = \frac{m_{yx}}{\dot{L}/\dot{V}}$
	$\beta_L a_{Ph} = C_L 12^{1/6} \bar{u}_L^{1/2} \left(\frac{D_L}{d_h}\right)^{1/2} a\left(\frac{a_{Ph}}{a}\right); \bar{u}_L = \frac{u_L}{h_L}$
	$\beta_V a_{Ph} = C_V \frac{1}{(\varepsilon - h_L)^{1/2}} \frac{a^{3/2}}{d_h^{1/2}} D_V \left(\frac{u_V}{a\nu_V}\right)^{3/4} \left(\frac{\nu_V}{D_V}\right)^{1/3} \left(\frac{a_{Ph}}{a}\right)$
	$\frac{a_{Ph}}{a} = 1.5(ad_h)^{-0.5} \left(\frac{u_L d_h}{\nu_L}\right)^{-0.2} \left(\frac{u_L^2 \rho_L d_h}{\sigma_L}\right)^{0.75} \left(\frac{u_L^2}{g d_h}\right)^{-0.45}$
	$h_L = \left(\frac{12}{g} \frac{\eta_L}{\rho_L} u_L a^2\right)^{1/3} \quad (u_V \leq u_{V,S})$
Sun et al. (11)	$(HTU_{OL})_{25^\circ C} = C \cdot L_W{}^D.$

Table 7. Parameters and deviations of HTU equations for packed column

			HTU	
Author	Packings	Parameters	S.D.	Avg.
Billet and Schultes (13)	Φ50 mm SMR	$C_L = 1.002$; $C_V = -1.163 \times 10^{-4}$	0.48%	1.0%
	Φ25 mm SMR*	$C_L = 0.838$; $C_V = -8.848 \times 10^{-5}$	0.74%	
	Φ16 mm SMR*	$C_L = 0.87$; $C_V = -5.848 \times 10^{-5}$	1.90%	
Sun et al. (11)	Φ50 mm SMR	$C = 0.200$; $D = 0.198$	0.54%	0.66%
	Φ25 mm SMR*	$C = 0.246$; $D = 0.193$	0.68%	
	Φ16 mm SMR*	$C = 0.24$; $D = 0.142$	0.75%	

*Experimental data from Sun et al. (11).

0.66% respectively. Therefore both models could be used in this study to predict the height of a mass transfer unit accurately.

CONCLUSIONS

The hydrodynamic and mass transfer models available for predicting performance in a SMR packed column have been studied over a wide range of operating conditions, including liquid loads up to $220\,m^3 \cdot m^{-2} \cdot h^{-1}$. A modified Billet and Schultes pressure drop equation has been presented for predicting pressure drop with SMR packings. Models for predicting the gas flooding velocities and the height of a mass transfer unit have also been presented and were shown to fit the experimental data well.

NOMENCLATURE

a	specified surface area of the packing $[m^2 \cdot m^{-3}]$
C_P, C_{Fl}, C_L, C_V	Billet and Schultes coefficients of the packing
d_S	diameter of the packing [mm]
g	gravitational constant $[m \cdot s^{-2}]$
h_L	liquid holdup $[m^3 \cdot m^{-3}]$
$h_{L,Fl}$	liquid holdup at flooding point $[m^3 \cdot m^{-3}]$
H	height of the packing section [m]
HTU	height of a transfer unit [m]
k_1, k_2, k_3, k_4, k_5, k_6	correction factor of the packing
L	mass flow of the liquid $[kg \cdot m^{-2} \cdot h^{-1}]$
$\dot{L}$	molar flow of the liquid $[kmol \cdot m^{-2} \cdot h^{-1}]$
L_W	liquid loads $[m^3 \cdot m^{-2} \cdot h^{-1}]$
NTU	number of transfer units
ΔP	pressure drop [Pa]
u	superficial velocity $[m \cdot s^{-1}]$
$u_{L,S}$	superficial liquid velocity at loading point $[m \cdot s^{-1}]$
$u_{V,Fl}$	superficial gas velocity at flooding point $[m \cdot s^{-1}]$
V	mass flow of the gas $[kg \cdot m^{-2} \cdot h^{-1}]$
$\dot{V}$	molar flow of the gas $[kmol \cdot m^{-2} \cdot h^{-1}]$

Greek Letters

β	mass transfer coefficient $[m \cdot s^{-1}]$
ε	void fraction of the packing $[m^3 \cdot m^{-3}]$
η	dynamic viscosity $[Pa \cdot s]$
θ	the corrected factor for Billet and Schultes model
λ	stripping factor
ρ	density $[kg \cdot m^{-3}]$
σ	surface tension $[kg \cdot s^{-2}]$

Subscripts

Fl	at the flooding point
L	liquid
V	gas
W	water

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